Performance and Dynamic Properties of an Active Axial Bearing

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Abstract

In magnetically levitated systems at least one degree of freedom has to be actively stabilized.[1] This is usually achieved with a linear magnetic actuator. If not prevented by e.g. lamination, eddy currents take place in the field conducting iron. These eddy currents have a strong effect on the field distribution in the iron and further reduce the force per current at higher frequencies. In this paper investigate the dynamic properties of a non laminated actuator biased with a permanent magnet in the rotor is anlaysed. It is shown that the voltage to force transfer function is practically unaffected by eddy currents.

1 Introduction

Active magnetic bearings are an essential part in magnetically levitated systems. We distinguish two main groups according to the mechanism of force generation. In the first the force is the result of the change in reluctance in the magnetic circuit and is therefore independent of the direction of the current in the coil. In the second, a permanent magnet in the magnetic circuit, which can be considered as constant current offset, results in a force dependent on the direction of the coil current. This allows a control loop around zero current, which is the main reason for choosing this type of active bearing.[2] It is advantageous to increase the performance by guiding the magnetic field in an iron core, as proposed by Jungmayr et al. [1], where the coil has been placed in the air gap of the magnetic circuit (called Lorentz force bearing). Beside the advantage of low inductivity, no negative stiffness and high linearity, it suffers from a low force per magneto motive force ratio k_Θ, due to the large air gap. Here we go one step further and enclose the coil with iron, such that the magnetic resistance is lowered, as shown in fig. 1. However, this has the drawback that the iron generates negative stiffness in the direction which has to be stabilized.[3] This negative stiffness is over compensated by the increase of the force per ampere turns.

In this paper a rotation symmetric (z-axis) setup which is passively stabilized in two planes perpendicular to the rotation axis (radial stable) with permanent magnet bearings (PMB's) is investigated. Thus the system is also stable against tilting. The remaining unstable degree of freedom is the z-direction. This is the direction in which the active bearing works. It has to, additionally to the negative stiffness of the active bearing, over compensate the negative stiffness of the PMB's. Furthermore, the stator is suspended by

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[1] We neglect here electrodynamic bearings and diamagnetic systems, since they play a minor role in technical applications.

[2] If there is an axial force at zero current in the planed equilibrium position, this force has to be compensated by other elements in the system, e.g. passive magnetic bearings.

[3] The directions perpendicular to this axis can be stable or unstable, depending on the geometry.

viscoelastic damping elements. These damping elements have a large influence on the control loop as shown by Jungmayr [2].

For rotational symmetric actuators lamination of the core is hard to accomplish.[4] As result eddy currents have a large effect on the field distribution, shown in fig. 1. Furthermore the performance parameter, i.e. force per magneto motive force, is strongly frequency dependent [3, 4, 5]. This can yield in bad dynamic behavior of the system.

It is shown that for these actuators the frequency dependence of $k_\Theta(f)$ is identical to the frequency dependence of the flux linkage per ampere $\psi(f)/i$. This allows the determination of the frequency dependence by a harmonic simulation without the permanent magnet, which is much faster than a transient simulation. If no saturation in the iron takes place it is possible to combine the results of the static and the harmonic simulation, as will be shown.

2 Finite element analysis

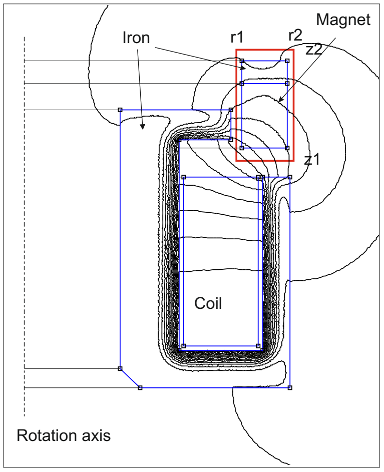

Figure 1: The investigated setup with the dynamic field distribution at 10Hz. The red rectangle denotes the integration path for the force calculation.

The analysis has been done with the finite element solver FEMM[6]. The iron was modeled linear with relative permeability $\mu_r = 4000$ and conductivity $\sigma = 10^6 \frac{S}{m}$. A NdFeB magnet with a remanence flux density of $B_r = 1.15T$ and a relative permeability $\mu_r = 1.065$ is used. Furthermore the conductivity of the magnet was neglected. The static analysis gives a value for the axial stiffness of $s_{ax} = -16 \frac{N}{mm}$ and a force per ampere of $k_i = 54 \frac{N}{A}$ for $N = 1200$ turns. The resistance of the coil is $R_{Cu} = 76\Omega$.

The dynamic calculations are done with the time harmonic solver of FEMM. The advantage of the time harmonic solver is that it is much faster than a transient solution, however with the drawback that nonlinear material properties, such as a nonlinear B-H curve, can not be easily included and permanent magnet magnetization is set to zero. The first drawback can be relaxed by choosing a design which does not saturate the material. This is also important to reduce losses. The second is overcome by the following procedure:

[4] A simple method to reduce eddy currents to a large extent, is to cut the iron at a certain angle ϕ.

After a static simulation with the permanent magnet, the field distribution on a path $\mathscr{C}$ around the rotor (which is still in the air gap) is saved, $B_r(r,z), B_z(r,z)$. The path consists only of horizontal and vertical lines, drawn in red in fig. 1, in order to simplify the calculation. The static force is calculated by integration of the Maxwell stress tensor on a surface enclosing the rotor

$$F_i = \int_{\mathscr{C}} \sum_j \sigma_{ij} dA_j \ . \tag{1}$$

Due to symmetry the ϕ- and r-component of the force vanishes. The ϕ integration in cylinder coordinates gives only a factor 2π. Thus for the horizontal lines

$$F^{(1)}_{z_{1,2}} = 2\pi \int_{r1}^{r2} \frac{1}{2\mu_0} (B_z^2(r, z_{1,2}) - B_r^2(r, z_{1,2})) r dr \tag{2}$$

and for the vertical lines

$$F^{(2)}_{z_{1,2}} = 2\pi r_{1,2} \int_{z1}^{z2} \frac{1}{\mu_0} B_z(r_{1,2}, z) * B_r(r_{1,2}, z) dz \tag{3}$$

is obtained. The force on the rotor is the sum of all contributions.

For the dynamic force we superimpose the dynamic- and the static- field distribution.

$$\mathbf{B} = \mathbf{B}^{\text{stat}} + \mathbf{B}^{\text{dyn}} \tag{4}$$

Note that this is only possible in the linear regime. Inserting the new field into the force calculation (2) and (3) we obtain three types of contributions:

- The sum of all terms where both fields are static yields the static force
- The sum of all mixed terms, i.e. $B^{\text{stat}}_{r,z} * B^{\text{dyn}}_{r,z}$, yields the dynamic force with frequency f
- The sum of all terms where both fields are dynamic yields a force with frequency $2f$ and is only a result of reluctance force on the small back iron of the magnet. This force is small and can be neglected in this case.

The dynamic field is complex valued due to the phase shift as result of eddy currents. This is also the case for the force. The result for the frequency dependence of the flux linkage and the force per magneto motive force is shown in fig. 2. It can be seen that the frequency dependence of both quantities are approximately identical. Descriptively this means that the field distribution outside of the iron looks similar for all frequencies, only the overall magnitude and the phase is changing. This similarity holds only under certain conditions: First no saturation effects take place and second the cross section of the flux path is designed to yield an approximately constant magnetic flux density.

2.1 Effects on the dynamics

A characteristic quantity is the frequency dependent flux linkage per ampere per turn:

$$L_1(f) = \frac{\psi(f)}{Ni}. \tag{5}$$

The frequency dependent part is isolated by dividing the static quantity

$$\lambda(f) = \frac{L_1(f)}{L_1(0)} \ . \tag{6}$$

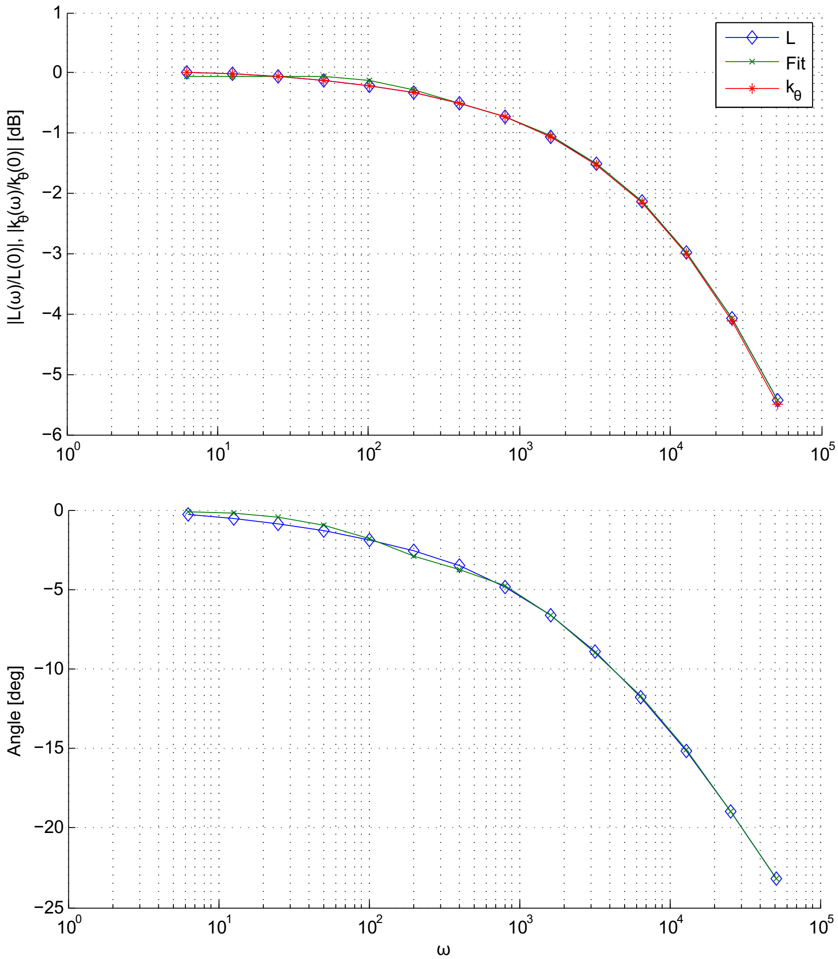

Figure 2: The frequency dependence of the flux linkage L (blue) and the force per magneto motive force k_θ (red) is shown. The FEMM results are fitted by a rational function of the order 5 in the nominator and denominator. (green)

The simulation results show that the frequency dependence of $k_\Theta(f)$ is identical and thus

$$k_\Theta(f) = k_\Theta(0)\lambda(f)\,. \tag{7}$$

This considerably simplifies the descripion of the system.

Next we look at the force as result of an applied voltage with frequency f, which is easily derived[5]

$$F(f) = k_\Theta(f)\, iN \tag{8}$$
$$= k_\Theta(f)\frac{U\,N}{R_{Cu} + \mathrm{j}\omega L(f)} \tag{9}$$
$$= k_\Theta(0)\lambda(f)\frac{U\,N}{R_{Cu} + \mathrm{j}\omega L(0)\lambda(f)} \tag{10}$$
$$= k_\Theta(0)\frac{U\,N}{\frac{R_{Cu}}{\lambda(f)} + \mathrm{j}\omega L(0)} \tag{11}$$

From (11) it is seen that $\lambda(f)$ has only an minimal influence on the Force response if the cutoff frequency of R_{Cu} and $L(0)$ is smaller than that of $\lambda(f)$, which is the case for the investigated system as shown in figure 3. This result should be a common effect for this type of bearing since the resistance of the coil R_{Cu} could be much higher (factor five) and also yield a similar result.

3 Control loop

In order to see the effect on the control system the closed loop transfer function is calculated. The same topology as proposed by Jungmayr et al. [2] is chosen, see fig. 4.

To quantify the stability of the system the transfer functions

$$T_{i,a}(\mathrm{j}\omega) = \frac{i(\mathrm{j}\omega)}{\ddot{\varepsilon}(\mathrm{j}\omega)} \tag{12}$$

and

$$T_{u,a}(\mathrm{j}\omega) = \frac{u(\mathrm{j}\omega)}{\ddot{\varepsilon}(\mathrm{j}\omega)} \tag{13}$$

are used. Two quantities which limit the stabilizeable external acceleration $\ddot{\varepsilon}$, the supplied voltage and the maximum current (thermal limited) are given. The result for the actual design (with elastically mounted stator) is shown in fig. 5. These results are compared to the calculation where eddy currents are neglected. It can be observed that the current limited acceleration is higher for the static calculation. This is expected since eddy currents reduce the dynamic stiffness [7].

The result for the voltage limited acceleration is surprising. From the similarity of the voltage to force transfer function one would expect that also the stabilizeable acceleration is approximately the same, for the case with and without eddy current. But this is not the case, the eddy currents decrease the maximal acceleration in the frequency range of 8-25 Hz. The reason lies in the topology of the control loop. The final current controller produce the error since the current is no longer proportional to the force due to eddy currents. To overcome the problem either the current (force) has to be corrected or a different design of the control loop has to be chosen.

4 Conclusion

It has been shown that the efficency of the bearing is lowered if eddy currents are not hinderd in circulation. This means that the force per current is reduced with increasing frequency.

[5]The induced voltage due to axial rotor movement is neglected.

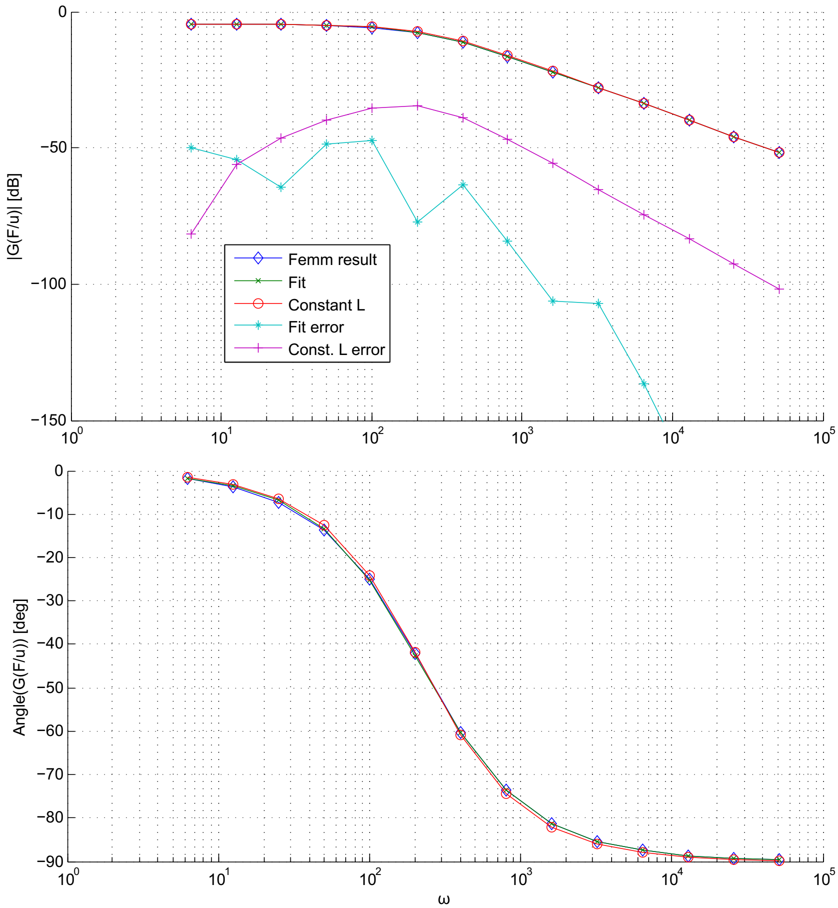

Figure 3: The voltage to force transfer function is shown. The FEMM result (blue) is compared with the fitted function (green), the error is ploted in cyan. The result with eddy currents is compared to the result where eddy currents are neglected (red). The difference is ploted in magenta.

On the other hand the voltage to force transfer function is in good approximation unaffected by eddy currents under certain conditions. These conditions are, no saturation effects take place and the cutoff frequency of the coil is lower than that of the eddy current. As result the control system topology could be changed, either to compensate the eddy current effects or choosing a topology which focuses on the voltage rather than the current.

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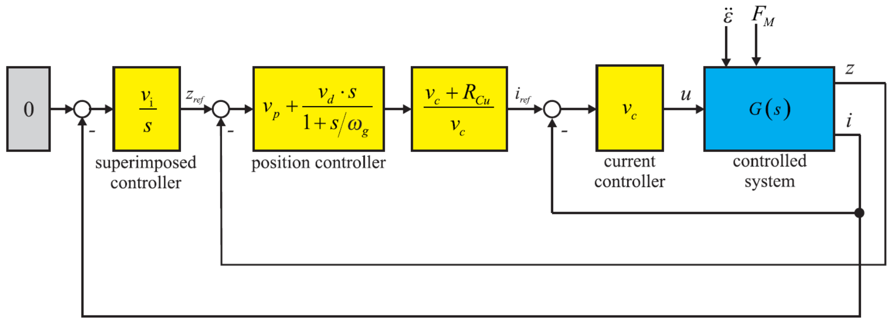

Figure 4: Control system as proposed by Jungmayr [2].

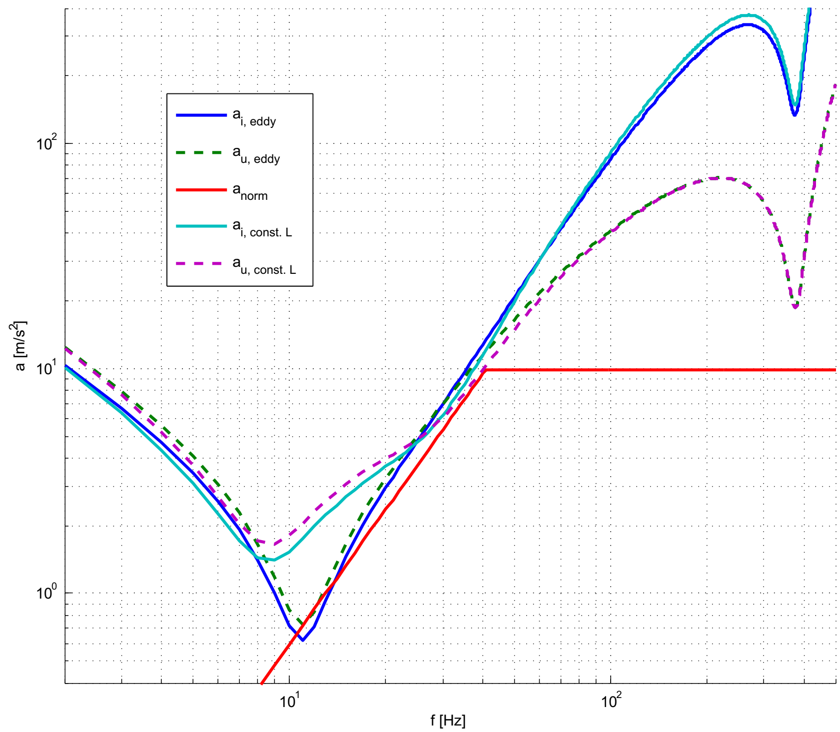

Figure 5: The frequency dependence of the stabilizeable acceleration is shown. The current (blue) and the voltage (green) limited acceleration with eddy currents is compared to the current (cyan) and the voltage (magenta) limited acceleration with constant L and k_θ i.e. without eddy currents. For clarity the voltage limited acceleration curves are dashed. These are compared to the 1g norm acceleration (red, IEC 60068-2-6:2007)

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